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"Novel Magnetic Devices"
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FINAL REPORT

a. EXECUTIVE SUMMARY

This project was dedicated to the development of novel magnetic devices relevant to applications in the fields of sensors, storage, non-volatile, reprogrammable spin-based electronics. The devices envisioned in this project explored novel physical phenomena and new functionalities not yet explored. More specifically, devices the initial idea was to explore three types of phenomena will be explored: ballistic magnetoresistance, magnetic field proximity effect and spin drag. These three phenomena would then be exploited for the design of novel device architectures and to investigate the physical principles behind these devices.

This project explored the design, preparation, measurement and theoretical study of these novel magnetic devices. Modern thin film techniques (sputtering and Molecular Beam Epitaxy) were used for the growth of the structures. These were combined with state-of-the-art photo and electron beam lithography to engineer the devices. Structural and chemical measurements at the nanoscale were used for characterization, and magnetotransport will be used to investigate their performance. Theoretical work input was used to design the most promising devices and to develop an understanding of the experimental results. More specifically the three general types of devices to be investigated have as key ingredients: Ballistic Magnetoresistance, Magnetic Field Proximity Effect, and Tunneling. These are novel devices that still require scientific basis to validate the science and to help further advances in technology.

Novel electronics that improve non-volatility, enhance storage, allow in-field programmability, and in general enhanced performances are of importance to DARPA. Our proposed research may have a major impact in areas related to data storage and manipulation and to the general area of sensors. In addition, the education of young researchers in these areas enhances the availability of qualified and trained personnel for the future scientific and technological infrastructure of the nation. Further funding is needed to complete many of the potentially very interesting projects.

b. TECHNICAL SECTION

1. ADVANCES IN THE FIRST TWO YEARS

Magnetic devices are becoming even more important for basic research. They have opened up the possibility of electronics with new functionalities and enhanced performance. These advances are the direct result of basic research on new magnetic phenomena and devices. Basic research has significant impact and relevance for the nation's economic and military well-being.

The general idea of this project is to compare three types of devices: ballistic weak links, field effect configuration, and trilayer devices. Each of these is based on different physical principles and is potentially important in the sensor or spin-based electronics areas. We started exploring the underlying physics and the design of specific geometries for each type of device.

2. BALLISTIC MAGNETORESISTIVE DEVICES (BMR)

Ballistic magnetoresistance (BMR) is the magnetoresistance arising from the propagation of electrons across a narrow domain wall without scattering. A number of experiments have been performed in small magnetic constrictions which seem to indicate the presence of a large magnetoresistance due to BMR. This effect was claimed in several elemental ferromagnets, alloys and even half metallic ferromagnets by others and there are even recent theoretical papers explaining these effects. All observations were made in structures that had ***macroscopic*** constituents and were built by using ***mechanical*** contacts. For instance, two sharp Ni tips were placed in physical contact by mechanical means. The observation of BMR has become quite controversial lately since many leading scientists attribute these results to motion associated with the unstable nature of mechanical contacts

In order to exploit BMR from a device point of view (or to make it useful in a variety of applications), it is desirable to implement this effect in mechanically stable, lithographically defined structures. So during the period of this project we investigated these types of devices. Also, this greatly facilitated controlled studies of a variety of physical properties such as dependences on constriction size, interface type, roughness, material, etc., which is important to enhance device performance and integration with other electronic components. This can be accomplished by preparing a variety of rigid structures using electron beam lithography techniques.

We developed two methods for the preparation of nanometric weak-links using combined electron beam lithography and ion milling. In the first method (see Figure 1), a number of ferromagnetic "fingers" are purposefully placed at slightly different distances from a perpendicularly oriented main ferromagnetic electrode. In this fashion, two major objectives are accomplished: a) preparation of very small constrictions independently of the ultimate control of the etching process and b) straightforward manipulation of the magnetic orientation of the fingers with respect to the main electrode. The final trimming of this device is done using ion milling with UHV *in situ* resistive measurements for feedback. This allows complete control over the size of the nanoconstrictions. An example of a device implemented by this method is shown in Figure 1.

The second method we implemented consists of the deposition of a pillar of a magnetic material through a nanometer scale hole made in a bi-layer resist (see Figure 2). First, a conducting base layer is deposited. Using e-beam lithography, a hole is patterned into a bi-layer resist that has been spun on top of the conducting base layer. In the final step, the magnetic material is deposited. The resistance in the "current perpendicular to the plane " geometry is monitored during deposition, which is stopped when the desired resistance is obtained. Contacts in the kΩ range were fabricated between the bottom disk-like electrode and the top thin film.

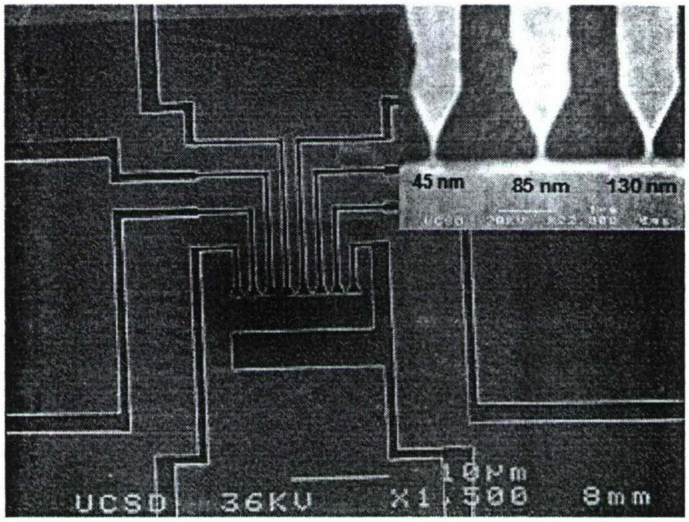

Figure 1. SEM picture of Co or Ni nanoconstrictions prepared by a combination of electron beam and photolithography. The inset shows the details of the nanocosntriction in a much expanded scale.

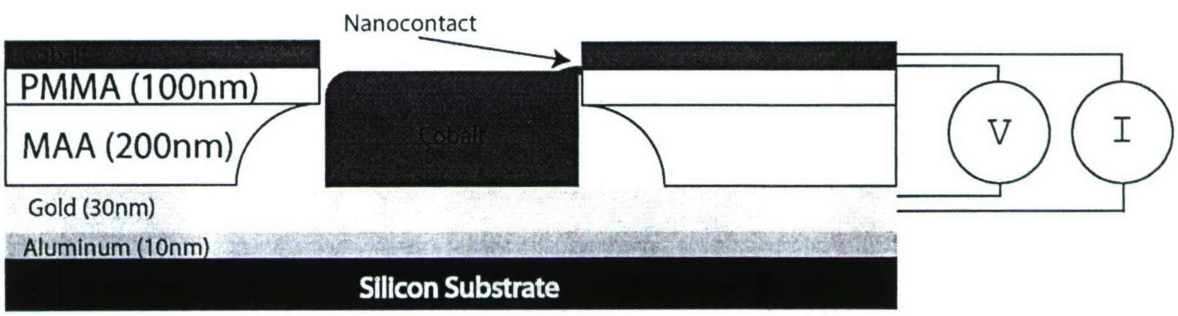

Figure 2. Preparation of nanocontact using a hole in an insulting membrane and monitoring the resistance during growth of a Co nanopilar.

These weak links, prepared by either of the two methods, are controllable and rigid. In addition, we developed further trimming of the electrode by using ion milling with a feedback loop using the actual device resistance as a control. In this fashion, we were able to implement controllable resistance devices and allowed performing quantitative measurements of the BMR and its dependence on device and material characteristics.

We performed a series of exhaustive measurements in these two configurations in a wide temperature (1-300K) and magnetic field (0-100kG) regimes to explore the possibility of large Ballistic Magnetoresistance. Resistance in the range $100\Omega - 20k\Omega$, of Co and Ni nanocostriction on Si, GaAs, and Al_2O_3 substrates were studied. Due to the large shape differences between the electrode materials, two distinct coercivities were observed indicating large differences in the switching fields of the two electrodes as designed. Unfortunately in all cases the magnetoresistances of varying signs were below 1% as expected from simple anisotropic Magnetoresistance. This implies that neither of these devices exhibits BMR as claimed earlier in non rigid structures.

Clearly, it is not possible to completely rule out the existence of BMR; i.e. it is impossible to prove that an effect does not exist. However, these measurements give a strong indication that if BMR exists at all as claimed earlier, it is of a very subtle and delicate nature; if this appears in some unique configurations at all, it has not yet been uniquely identified. Therefore, further research is needed to either discard this effect or to determine under what conditions the effect is present.

3. MAGNETIC FIELD EFFECT DEVICES (MFED)

We have started preparing a set of new devices that would give rise to MFEDs. The types of devices that have been already designed and built are shown in Figure 3.

The device was prepared using thin film deposition using magnetron sputtering and electron beam evaporation, photolithography and electron beam lithography. Our first generation devices (see Figure 3) was developed using a large area trilayer Al/AlOx/Co structure, which was subsequently sectioned with ion milling techniques into parallel lines. In this fashion, we define the source and drain electrodes. Photolithography was then used to define Co gate lines perpendicular to the Al source-drain lines. A final ion milling step was used to remove all the Co that was part of the original trilayer structure except for the regions where the Al and Co lines intersect. The reason that such a complex structure is needed is because it is important to retain the original Co in the region of the junction in order to preserve the integrity of the barrier; chemicals from processing could otherwise degrade the tunnel junction quality. The resulting device has Al/AlOx/Co tunnel junctions separated by a certain distance along the Al source-drain line (see Figure 3b). Extension of this devices using high-end electron beam lithography are currently underway and measurements have just started.

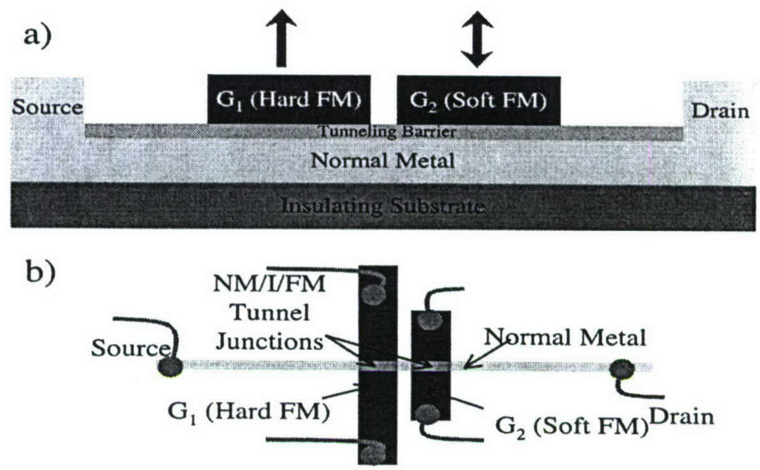

Figure 3. Proposed device architecture cross section (a), and top view (b). The two ferromagnetic gates (cobalt) are isolated from the normal metal conduction channel (aluminum) by a tunneling barrier (aluminum oxide). The gates can be deposited in appropriate geometries to give them discrete coercivities, thereby rendering one hard and one soft. For this particular effect, no voltage needs to be applied to the gates, though that addition to our parameter space will be explored.

The fabrication of high quality tunnel junctions between the gates and the channel is crucial because the barrier will effectively isolate the source-to-drain current from the ferromagnets. This is of utmost importance because if current is allowed to pass through the ferromagnets, then this experiment will be simultaneously measuring several phenomena, including the anisotropic magnetoresistance of the individual gates, the giant magnetoresistance effect mediated by transport of electrons from one gate into the other, and, for those electrons that stay in the normal metal channel, the ferromagnetic proximity effect. Experiments by others on systems without tunnel junctions have been performed but have received significant public criticism. Therefore, we spent considerable amount of effort to understand the behavior of tunnel junctions with these electrodes and the effect of pinholes on the I-V characteristics.

This was a new project, which lasted only for two years. Consequently, much of the work is still underway and several publications are in the writing process. Accelerated output is anticipated if further funding is obtained.

c. PUBLICATIONS

1. *Deep Oxidation of Aluminum by a DC Oxygen Plasma*, J. A. Baier-Saip, A. L. Cabrera and I. K. Schuller, Surf. Coat. Tech. 195, 168 (2005).
2. *Magnetoresistance of Mechanically Stable Nanoconstrictions*, M. I. Montero, R. K. Dumas, G. Liu, M. Viret, O. M. Stoll, W. A. A. Macedo and I. K. Schuller, Phys. Rev. B 70, 184418 (2004).
3. *Bias Dependent Oscillations in Spin Polarized Tunneling,* Casey Miller, Johan Åkerman, Zhi-Pan Li, and Ivan K. Schuller, Bull. Am. Phys. Soc. 51, 1337 (2006).
4. *Evidence for WKB Failure in Contemporary Magnetic Tunnel Junctions,* Casey W. Miller, Z.-P. Li, Ivan K. Schuller, R.W. Dave, J.M. Slaughter and J. Åkerman, 10th Joint MMM/Intermag Conference MMM 2007, January 7-11, 2007, Baltimore.
5. *Time Dependent Ginzburg-Landau: from Single Particle to Collective Behavior*, I. K. Schuller and K. E. Gray, Jour. Supercond. Novel Mag. 19, 401 (2006).
6. *Origin of the Breakdown of Wentzel-Kramers-Brillouin-based Tunneling Models*, C. W. Miller, Z.-P. Li, I. K. Schuller, R.W. Dave, J. M. Slaughter and J. Åkerman, Phys. Rev. B 74, 212404 (2006).
7. *Impact of Interfacial Roughness on Tunneling Conductance and Extracted Barrier Parameters*, C. W. Miller, Z.-P. Li, J. Åkerman and I. K. Schuller, Appl. Phys. Lett. 90, 043513 (2007).
8. *Relaxation Processes in Micromagnetics*, Harry Suhl, International Series of Monographs on Physics 133, Oxford University Press, New York, 2007.

d. INVITED TALKS

1. *Magnetoresistance of Rigid Nanometer Sized Constrictions*, Ivan K. Schuller, Anaheim, California, 9th Joint Intermag Conference, January 5-9, 2004.
2. *Emerging Areas of Magnetism in Confined Structures*, Ivan K. Schuller, Workshop on Nanomagnetism Using X-ray Techniques, Lake Geneva, Wisconsin, August 30, 2004.
3. *Nanostructured Magnetism: Confinement, Proximity, and Induced Phenomena,* Ivan K. Schuller, 2nd US-Japan Workshop on Synchroton Radiation and Nanoscience, San Diego, California, April 4-6, 2005.
4. *Nanostructured Magnetism*, Ivan K. Schuller, I. V. Roshchin, C.-P. Li, M. Montero, R. Morales, O. Petracic, S. Roy, Z.-P. Li, X. Batlle, S. K. Sinha, M. R. Fitzsimmons, J. Villegas, and J.-L. Vincent, Magnetism Magnetic Materials (LAW3M05), Viña del Mar, Chile, December 11-15, 2005.
5. *Nanomagnetism,* Ivan K. Schuller, Pan America Advanced Study Institute, PASI 2007, Zacatecas, Mexico, June 19, 2007.